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The Effect of Tactile Cues on Auditory Stream Segregation Ability of Musicians and Nonmusicians

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Difficulty perceiving music is often cited as one of the main problems facing hearing-impaired listeners. It has been suggested that musical enjoyment could be enhanced if sound information absent due to impairment is transmitted via other sensory modalities such as vision or touch. In this study, we test whether tactile cues can be used to segregate 2 interleaved melodies. Twelve musicians and 12 nonmusicians were asked to detect changes in a 4-note repeated melody interleaved with a random melody. In order to perform this task, the listener must be able to segregate the target melody from the random melody. Tactile cues were applied to the listener's fingers on half of the blocks. Results showed that tactile cues can significantly improve the melodic segregation ability in both musician and nonmusician groups in challenging listening conditions. Overall, the musician group performance was always better; however, the magnitude of improvement with the introduction of tactile cues was similar in both groups. This study suggests that hearing-impaired listeners could potentially benefit from a system transmitting such information via a tactile modality.

Keywords: auditory stream segregation, multimodal perception, auditory–tactile interaction, music

Western music is often composed of multiple melodic streams that combine to produce a complex structure that gives a particular piece its unique depth and quality. In order to appreciate the interplay of melodic streams, listeners need to be able to first segregate them. Unfortunately, people with hearing loss typically experience great difficulty in doing so primarily due to an impoverishment of their perceptual cues (Oxenham, 2008). This makes music appreciation very challenging for these listeners. For hearing-impaired people whose auditory pathway is fundamentally limited, such as those who use a cochlear implant, it is important to explore sensory substitution as a possible means of enhancing stream segregation and music perception. Recent studies have shown that visual cues can aid hearing-impaired people, and more specifically cochlear implant listeners, in better segregating two musical streams (Innes-Brown, Marozeau, & Blamey, 2011; Marozeau, Innes-Brown, Grayden, Burkitt, & Blamey, 2010). We therefore hypothesize that tactile information can be used in a similar way.

This paper describes a first study which tests the effect of tactile cues on segregation ability in normal hearing listeners as function of their musical background.

Segregation of a melodic stream is made possible by both bottom-up and top-down processes. Bottom-up processes are derived from perceptual cues such as pitch, timbre, and loudness (Bregman, 1990; Marozeau, Innes-Brown, & Blamey, 2010). Top-down processes are derived from cognitive processes involving memory, expectation, musical training, and attention (Carlyon, Cusack, Foxton, & Robertson, 2001). Auditory stream segregation can also be influenced by cross-modal interaction (Carlyon, Plack, Fantini, & Cusack, 2003). Marozeau et al. (2010) have demonstrated that visual cues can improve the streaming ability in both musicians and nonmusicians. Carlyon et al. (2003) has also demonstrated both cross-modal and nonsensory influences on auditory streaming.

It is not uncommon for a listener to describe the sensation of “feeling music.” Tactile information can add to temporal cues emphasizing the rhythm within a piece (Fraisse, 1981), and can generate a strong sensation of rhythm on its own (Brochard, Touzalin, Després, & Dufour, 2008). Huang, Gamble, Sarnlert-sophon, Wang, and Hsiao (2013) demonstrated that meter is perceived similarly well (70%–85%) when either tactile or auditory cues are presented alone, and that in bimodal mode auditory and tactile cues are integrated to produce coherent meter percepts. It might therefore be hypothesized that tactile information can have an effect on the perception of the musical streams.

Musical training is known to have a positive effect on segregation ability (Strait, Kraus, Parbery-Clark, & Ashley, 2010). The effect of cross-modal information on stream segregation can therefore interact with musical training. In order to isolate and under-

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stand the interaction between tactile cues and auditory stream segregation ability normal hearing listeners with and without musical experience were assessed.

Method

Participants

Twenty-four participants (12 musicians and 12 nonmusicians, with approximate age average of 27 years old, ranging from 21 to 35 years old) were recruited using social networks in the musician and nonmusician communities. All musicians were full-time professional performers. Nine of them had a formal tertiary education in music and could read music proficiently. The other three were professional flamenco players with an expert level of musicianship but a weaker ability to read music. All the nonmusician participants were unable to play an instrument, and had limited musical training. All participants reported normal hearing and had hearing thresholds at octave frequencies from 125 Hz to 8 kHz below 20 dB HL. Participants also reported normal tactile sensation in their fingertips. The level of the tactile stimuli was set by slowly increasing the intensity until the participant reported a clear tactile perception. There was no auditory perception induced by the actuator. Travel and lunch expenses were reimbursed (\$20 AUD). The experimental protocol conforms to The Code of Ethics of the World Medical Association (Declaration of Helsinki), and was approved by the Human Research Ethics Committee of the Royal Victorian Eye & Ear Hospital (Project 09-880H). Written informed consent was obtained from all participants involved in the study.

Stimuli

Auditory stimuli. Matlab 7.5 was used to construct the melody and distractor notes. Each note consisted of a 180-ms complex tone with 10 harmonics, and included a 30-ms raised-cosine onset and 10-ms offset. Successive harmonics in each tone were attenuated by 3 dB. MAX/MSP 5 was used to control the delivery of these notes, which were sent to an M-AUDIO Firewire 48-kHz 24-bit sound card. The auditory stimulus was produced by a loudspeaker (Genelec 8020APM) positioned on a stand at the listeners' ear height, 1 m from the listeners' head. Each note was equalized in loudness to 65 phons according to a loudness model defined by the American National Standards Institute (ANSI, 2007).

The participants were exposed to a series of notes with each note onset presented every 200 ms. Within this series of notes was a repeated four-note target melody and interleaved distractor notes. A new target melody was created for each participant by picking randomly four notes without repetition from the octave above middle C. The four notes were ordered from lowest to the highest note, and then the two middle notes were inverted in order to create

the same melodic contour for each participant (up, down, up, down). Each distractor note value was randomly chosen from a pool of consecutive notes spanning a 12-tone-equal-temperament octave (see Figure 1 for an example).

Tactile stimuli. A vibro-tactile stimulus was generated using commercially available piezoceramic transducers driven with a 30 Hz sinusoidal signal. This signal was generated using an Agilent 33220A signal generator, and a simple amplifier made using an LM741 opamp that boosted the signal to 10Vpk-pk. This amplitude was necessary to generate a robust suprathreshold vibration. A multiplexer was used to route this signal to one of eight transducers. This ensured that at most only one transducer could be activated at any given time. These eight transducers were embedded in a rectangular gel pad, and positioned to accommodate a range of hand sizes while maintaining a comfortable hand position (see Figure 2). The transducers were controlled using an ARDUINO ATMEGA128 development board. This system connected directly to the host PC via USB. This enabled integration with MAX/MSP 5.

For this experimental paradigm only four of the eight transducers were utilized. Each of these four transducers was assigned to a note of the 4-note target melody. Each time a note in the melody was played, the corresponding transducer was activated. No tactile stimulation was presented with the distractor notes. The transducers were assigned tonotopically, with the note with the lowest pitch corresponding to the little finger of the left hand, and the note with highest pitch corresponding to the little finger of the right. The synchronization of the auditory-tactile cue was measured by using a single transducer as both a vibro-sensor and a microphone. This enabled detection of the delay between the tactile and acoustic stimuli. The synchronization could be controlled by introducing a delay in the firmware of the ATMEGA128 development board. Two switches were mounted on the face of the pad, and were easily accessed by the left and right thumbs. This provided convenient response buttons without the subject needing to reorient their hands.

Procedure

Two sessions were run for each participant—one with the tactile cue present (Tactile) and one without (No-tactile). In each of these sessions, the participants were asked to listen to a four-note target melody that was repeated in a loop. At random times within this looping melody, two notes of the melody were inverted, creating a deviant melody (see Figure 1). The participant was asked to press the response button when they detected this change. The difficulty of this task was increased by introducing interleaved distractor notes that made it more difficult to segregate the target melodic stream. The distractor notes were attenuated by 0, 6, and 12 phons relative to the melodic stream. Prior to testing, the 4-note melody was presented 20 times without distractor notes to ensure partici-



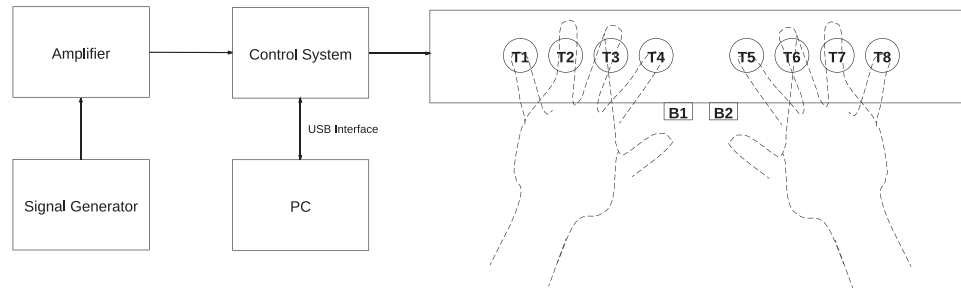


Figure 2. Tactile stimulus control unit and actuator.

pants were familiar with the target melody. The probability of a deviant being presented in a given bar was set to 12.5%. Once a deviant melody was presented, no other deviant could appear for at least 3 bars. The experiment stopped when 20 deviants were presented. Overall each trial lasted on average 143 bars, with a standard deviation of 13 bars. It is important to note that the tactile stimulus sequence associated with the target melody was applied during this training period. Also, this tactile pattern was kept constant when the target melody deviated, creating a temporary mismatch between the tactile and audio stimuli.

Results

Subject Performance Evaluation

Participant responses were categorized as hit, miss, false alarm, or correct rejection corresponding to correct detection of deviant melody, deviant melody not detected, detection without presence of deviant melody, and no detection when standard melody was presented. From these four categories, only hits and false alarms were needed to describe the subject performance, which was done by calculating an indicator of the individual performance d' .

First, the number of hits was divided by the total number of bars containing a deviant and the number of false alarms was divided by the total number of bars containing a target melody. Then d' was calculated by subtracting the z -scores of these two quantities, as described in equation (1). The greater d' , the better the participant performance.

$$d' = Z(\text{Hit rate}) - Z(\text{FA rate}) \quad (1)$$

It is important to notice that due to the z -score transformation, d' would take values of $+\infty$ and $-\infty$ when the hit or false alarm rates are either 1 or 0. To solve this indeterminacy, hit or false alarm rates of 1 and 0 were limited for 0.99 and 0.01, respectively.

Description of Data

A total of 288 observations were made, corresponding to the 24 participants performing all six combinations of attenuation levels and tactile conditions twice. This was averaged to produce a dataset of 144 points. Figure 3 shows the overall subject performance for musicians and nonmusicians for each of the six conditions.

The subject performance is seen to increase with attenuation level for both groups, which was expected since the task was made substantially easier when the loudness of the target melody was

relatively louder. Overall the musicians show a higher d' than the nonmusicians. Despite the fact that d' values for the tactile condition seem to be slightly greater than the ones for the audio only condition, the effect of the tactile cues is not as clear. A mixed linear model was fitted to the data using the statistical software R (R Core Team, 2015) and the package lmerTest. A first model was built including three main fixed effects: the group (musicians and nonmusicians), condition (tactile and nontactile), and the attenuation level (0, 6, and 12 phons). The participants were added as a random effect. All possible interactions were considered to begin with, then nonsignificant random and fixed effects as well as their interactions were removed from the model based on an automatic backward elimination method as implemented in the function STEP of lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2015). A second model was built with only the following fixed effects: group, condition, attenuation level, and its interaction with condition; and the following random effects: participant and its interaction with the attenuation level.

$$d' = \text{group} + \text{cond} + \text{level} + \text{cond}:\text{level} + (\text{participant}) + (\text{participant}:\text{level}) + \text{error}$$

The attenuation level of the distractor notes, which was the variable used to control the difficulty of the tasks, was expected to

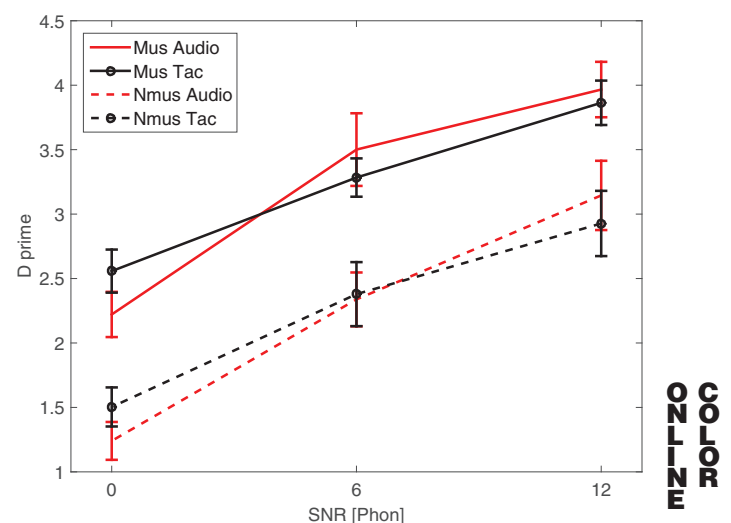


Figure 3. Musician and nonmusician subject performances for each condition. The error-bars represent ± 1 standard deviation. See the online article for the color version of this figure.

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have a great impact on subject performance. The analysis revealed a significant main effect of the level, $F(2, 46) = 89.02$; $p < 0.001$, $\eta^2 = 0.14$, confirming that the scores increased with higher signal to noise ratio (SNR). Musical training was also shown to have a significant effect on subject performance, $F(1, 22) = 18.18$; $p < 0.001$, $\eta^2 = 0.01$. This was consistent with previous literature (Micheyl, Delhommeau, Perrot, & Oxenham, 2006), which has previously shown musicians present systematically higher performance in a variety of tasks. On average, musicians obtained a d' that was 1.17 higher than nonmusicians.

The effect of condition was found to be nonsignificant, $F(1, 69) = 0.81$; $p = 0.373$; however, the interaction between attenuation level and condition was found to be significant, $F(2, 69) = 3.73$; $p = 0.029$, $\eta^2 = 0.01$. This significant interaction can be observed in Figure 3, which shows a steeper slope for the audio-only condition compared with the audio-tactile condition. This suggests that the audio-only condition is more affected by the change in SNR. Post hoc analysis, using a multivariate T test correction as implemented in the “lsmeans” package (R Core Team, 2015), revealed significant effect across condition only in the most demanding listening condition of 0 phon SNR, with an improvement in d' values of 0.31, $t(69) = -2.45$, $p = 0.0493$. Subject performance was not significantly different with or without tactile cues for attenuation levels of 6 or 12 phon SNR, $t(69) = -0.52$, $p = 0.937$, and $t(69) = 1.41$, $p = 0.408$, for attenuation levels of 6 and 12 phon, respectively.

Discussion

The main aim of this study was to test whether tactile cues can improve the melodic stream segregation ability of normal listeners. This aim was motivated by the possibility to partly restore music appreciation in hearing-impaired listeners. Although the analysis did not reveal any significant main effect of the tactile cues on stream segregation, a post hoc analysis revealed that the tactile cues can help in difficult situations. This would therefore suggest that the tactile cues might be beneficial for hearing-impaired listeners who experience difficult listening situations more often. For example, a cochlear implant user will typically find it difficult to perceive speech presented with a noise at + 5 dB SNR, which is a trivial task for normal hearing listeners.

The analysis also reveals a significantly steeper slope for the audio-only condition compared with the audio-tactile. It is interesting to note that at high SNR (with the noise attenuated by 12 phons), the average d' for the audio-only situation is higher for both groups than the average d' for the audio-tactile condition. Although the effect is not significant, it might indicate that the tactile stimuli can have a detrimental effect on the detection task. One has to keep in mind, that even when the melody was inverted the tactile input did not change insuring the detection task was not based on tactile cues alone. Therefore, at high SNR, it is possible that listeners were influenced by the tactile cues, and did not report the deviants accurately.

A large and significant difference between the musicians and nonmusician groups at every SNR was also observed in analysis. This difference was expected at 0 SNR, as it reproduced the outcome of previous experiments using similar protocols (Marozeau et al., 2010). It was, however, surprising to observe similar differences at high SNR. For example, when the distractors were

attenuated by 12 phons, enabling clear perception of the target melody, the task should have been fairly easy even for nonmusicians. There are two main factors that could explain the improved performance of the musician group at every SNR. First, musicians typically have better auditory memory. This helps them to better memorize the target melody and identify deviations. It is interesting to note that, as the melodies could be atonal and could include significant jumps, it was not always easy to memorize them. Second, it is also possible the musician group simply felt a higher motivation to perform the task well.

As the tactile information was only presented in synchrony with the melody note, the contribution of the spatial congruence of the stimulus is unclear. One might argue that a single tactile stimulus that vibrates with all the melody notes will induce the same small effects. On the other hand, it might have been important that each actuator was associated to a specific note and finger, and that this association mimicked a piano keyboard layout: the lower notes were located on the left and the higher ones on the right. As piano players have built strong neuronal connections between the motor movement of each finger and pitch, such a configuration might have created for them a strong cue to enhance auditory segregation. However, some musicians learn different spatial mappings. For example, flutists associate the right most keys as low notes, and the left ones as high notes; double bass players associate a high hand position with low notes, and low hand positions with high notes. To test this specific hypothesis, further experiments are needed with different types of tactile stimuli, and musicians.

Finally, it is interesting to see that the score differences between musician and nonmusician groups decreased by ~20% when comparing the score of the musician/audio-only condition with the nonmusician/audio-tactile condition. This suggests that the benefit of the tactile cues for nonmusicians in this specific paradigm can be considered as about 20% of the benefit of intensive music training.

Overall, this study suggests that tactile cues could potentially help hearing-impaired listeners to better segregate musical streams, thus potentially increasing their enjoyment of music. However, as the effect observed is fairly small, more research is needed to optimize this cue.

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